HIDDEN SECTOR AXIONS: PHYSICS AND COSMOLOGY*

HANS PETER NILLES
Physikalisches Institut, Universität Bonn, D-53115 Bonn, Germany
E-mail: nilles@th.physik.uni-bonn.de

Embedding hidden sector supergravity models in the framework of string theory leads to the appearance of axion-like degrees of freedom. Among them is the model independent axion of heterotic string theory. It has a decay constant of order of the Planck scale and could play the role of a quintessence field. In models allowing for the required μ term in the TeV range, the hidden sector dynamics leads to a vacuum energy of $(0.003\ \mathrm{eV})^4$ via a multiple see-saw effect. A solution to the strong CP-problem is provided by an additional hidden sector pseudoscalar with properties that make it an acceptable candidate for cold dark matter of the universe.

Supersymmetry might play an important role in stabilizing the weak scale (of order TeV) against uncontrolled radiative corrections. Therefore the mechanism of supersymmetry breakdown is one of the major problems in model building. It soon became clear that supersymmetric extensions of the standard model require supersymmetry breakdown in a hidden sector. In its simplest and compelling form, hidden and observable sector are coupled extremely weakly via interactions of gravitational strength. The original scheme[1] incorporated hidden sector supersymmetry breakdown via gaugino condensation[2,3]. Susy breakdown by the Polonyi mechanism[4] was subsequently discussed in[5,6,7]. The weak scale (represented by the gravitino mass $m_{3/2}$) and the Planck scale $M_{\rm Pl}$ are connected via a see-saw mechanism

$$m_{3/2} \sim \frac{M_{\rm SUSY}^2}{M_{\rm Pl}}, \qquad (1)$$

where $M_{\rm SUSY} \sim 10^{11}$ GeV is the source of spontaneous supersymmetry breakdown.

This scheme has a beautiful embedding in the framework of the $E_8 \times E_8$ heterotic string[8]. The interplay of the 3-index antisymmetric tensor field strength and the gaugino condensate in the hidden E_8 sector[9,10,11] allows the breakdown of supersymmetry. In the heterotic M-theory of Horava and Witten[12] the mechanism persists and the hidden sector obtains a geometrical interpretation[13,14,15]. For a review and references see[16,17].

These higher dimensional string theories contain many more fields that might be relevant for the physics at scales far below the string scale, particularly a set of pseudoscalar fields that could be candidates for light axions. In

*TALK GIVEN AT SUGRA20, THE INTERNATIONAL CONFERENCE 20 YEARS OF SUGRA AND SEARCH FOR SUSY AND UNIFICATION, NORTHEASTERN UNIVERSITY, BOSTON, USA, MARCH 2003

the heterotic theory there appears the so-called model independent axion[18], the pseudoscalar partner of the dilaton. This axion might be problematic as the corresponding axion decay constant is expected to be of the order of string and Planck scale, causing trouble with a non-zero and large contribution to the vacuum energy density of the universe[19]. Other axions might be useful as a solution to the strong CP-problem and/or candidates for cold dark matter in the universe.

Meanwhile the Type 1a supernova observation of nonzero dark energy [20] makes us believe that the vacuum energy of the universe is nonzero at a value of approximately $\lambda^4 \sim (0.003 \text{ eV})^4$. This has (re)created a lot of interest in quintessence models[21,22,23,24,25]. All these models try to account for the presently observed dark energy, but they differ in the prediction of future dark energies.

In the present talk we want to suggest that the model independent axion mentioned above could play the role of such a quintessential particle (quintaxion) that explains the size of dark energy currently observed[26]. Models with hidden sector gaugino condensation are shown to contain a (multiple see-saw) suppression mechanism for the scalar potential that leads to $\lambda^4 \sim (0.003 \text{ eV})^4$. One of the reasons for this suppression is related to the mechanism to solve the so-called μ problem of the Higgs mass parameter in supersymmetric models. The large value of the axion decay constant is now responsible for the fact that the quintaxion has not yet settled to its minimal value, thus giving rise to the dark energy observed. The model considered contains a second (hidden sector) axion, that mixes with the model-independent axion. One linear combination of the two then plays the role of the quintaxion, while the second is the invisible QCD-axion for the solution of the strong CP-problem that simultaneously provides a source for cold dark matter. This mechanism works because of some interesting relations between the mass scales of the model, on one hand the similarity of the scale of supersymmetry breakdown and the scale of the QCD axion, on the other hand the coincidence of the vacuum energy and the mass of the QCD axion. The quintaxion has an extremely small mass of the order 10^{-32}eV given by $\lambda^2/M_{\rm Planck}$.

Such ultra-light pseudo-Goldstone boson have been discussed earlier [21,22,23] in different contexts. In Ref.[21], the mass of the boson was related to the neutrino mass through m_ν^2/f. In Ref.[22,23], the mass coincided with the almost massless hidden sector quark(s). These models need the decay constant around $> 10^{17}$ GeV so that the universe has not yet relaxed to the minimum of the potential[21]. If one parametrizes this potential as

$$V[\phi] \sim \lambda^4 U(\xi), \quad \xi = \frac{\phi}{f}, \tag{2}$$

the parameter $\omega = p/\rho$ is expressed as $\omega = (\frac{1}{2}\dot\phi^2 - V)/(\frac{1}{2}\dot\phi^2 + V)$. The evolution equation of the quintaxion, $\ddot\phi + 3H\dot\phi + \frac{\partial V}{\partial \phi} = 0$, gives rise to a particular

equation of state. We are interested in the state where $\ddot{\phi}$ is negiligible, and obtain

$$\omega \simeq \frac{-6f^2 + M_P^2 |U'|^2}{6f^2 + M_P^2 |U'|^2} \tag{3}$$

where $M_P = 2.44 \times 10^{18}$ GeV is the reduced Planck mass and $U' = \partial U / \partial \xi$. The quintessence condition $\omega < -\frac{1}{3}$ requires that $f > \frac{M_P}{\sqrt{3}} |U'|$. For example, if $f \simeq 10^{17}$ GeV, the potential of the form $-\cos\xi$ requires $\xi = [\pi - 0.07, \pi + 0.07]$ which may not be considered as a fine-tuning. For a larger value of f this range is even increased [a]. This shows that natural quintessence requires f near the reduced Planck scale, and the mass of the quintaxion to be around 10^{-32} eV. Depending on the specific properties of the model under consideration such a field might be detectable through its cosmological effect of rotating the polarization state of radiation from distant sources[27].

The models studied in Ref.[22,23] rely on standard axion physics [28] which we are going to present here for completeness. The axionlike boson a_q generates a tiny potential. In QCD, we know that if there exists a very light up quark u then the instanton induced θ dependent free energy has the form

$$-m_u \Lambda_{QCD}^3 \cos\bar{\theta} \simeq -m_\pi^2 f_\pi^2 \cos\bar{\theta} \tag{4}$$

where $\bar{\theta}$ and Λ_{QCD} are the QCD vacuum angle and the QCD scale. By making m_u small, one can shrink the instanton induced potential. In Refs. [22], this fact was observed but not applied to a specific model. In these models with ultralight pseudo Goldstone bosons, it was assumed that the cosmological constant problem(CCP)[29,30] is solved by some as yet not understood mechanism such as the self-tuning solutions[31] or as a consequence of a symmetry [b]. Because a_q is a pseudo-Goldstone boson, the difference between the maximum and minimum points of the a_q potential is 2 in units of the explicit breaking scale(of order $(0.003\text{ eV})^4$) of the global symmetry. The solution of the CCP is expected to be achieved at an extremum point such that equations of motion determine the vanishing cosmological constant.[c]

In Ref. [22,23], it was attempted to interpret a model-dependent axion as the ultra light pseudo Goldstone boson. In this talk, however, we attempt to interpret the *model-independent axion(MI-axion)*[18] in superstring models as the quintaxion candidate.

The MI-axion a_{MI} is the pseudoscalar field present in the two form field B_{MN} $(M, N = 0, 1, 2, \cdots, 9)$: $\partial_\mu a_{MI} \sim \epsilon_{\mu\nu\rho\sigma} H^{\nu\rho\sigma}$ $(\mu, \nu = 0, 1, 2, 3)$ where H

[a] Due to the large value of f, the potential is extremely flat and the axion is frozen at its initial value and thus has not moved in the recent past of the cosmological history

[b] In the present paper we adopt the same attitude towards the solution of the CCP.

[c] Here, we assume that the zero cosmological constant is reached from above, i.e. in a de Sitter space. Recently, it has been argued that it is reached from below, i.e. in an anti de Sitter space[32]. In this case also, our argument applies.

is the field strength of B. In models with an anomalous $U(1)$ gauge symmetry, this MI-axion is removed from the low energy spectrum and there is no pseudoscalar degree for quintessence. On the other hand, if there does not exist such an anomalous $U(1)$ gauge symmetry then the MI-axion survives down to low energy. But it was noted that there would appear a cosmological energy crisis [33] of the MI-axion if it were the QCD axion, since the decay constant is near the Planck scale. However, if the potential for the MI-axion is made very flat so that the universe has not rolled down the hill yet, then the energy density explains the presently observed dark energy. So the superstring models without the anomalous $U(1)$ gauge symmetry belong to the class of models we discuss here.

In the gravity mediated supersymmetry breaking scenario via the hidden sector gaugino condensation, the mass of the hidden sector gaugino is of order TeV. The height of the hidden sector instanton induced potential depends on this gaugino mass. Note that the current quark mass m_u appears in the coefficient of instanton induced potential (4). This happens because the chiral transformation $u \to e^{i\gamma_5\alpha}u$ is equivalent to changing the coefficient of the anomaly term by $\bar{\theta} \to \bar{\theta} - 2\alpha$. Thus, this symmetry manifests itself through the appearance of the current quark mass in Eq. (4). Similarly, with gaugino condensation in the hidden sector, the hidden sector gaugino mass appears in the coefficient of the instanton induced potential and hence can influence the height of the potential significantly in particular for a large hidden sector gauge group, as we shall see explicitely in the following.

Suppose that the hidden sector gauge group is $SU(N)_h$ and there are n pairs almost massless hidden sector quarks and anti-quarks, transforming like the (anti-)fundamental representation of $SU(N)_h$. Then, the coefficient of the hidden sector instanton induced potential is

$$\lambda_h^4 \equiv m_Q^n m_{\tilde{G}}^N \Lambda_h^{4-n-N}. \tag{5}$$

where $\Lambda_h \simeq 10^{13}$ GeV is the hidden sector scale and $m_{\tilde{G}}$ is the hidden sector gaugino mass.

Let us now discuss some illustrative examples for the conditions between m_Q, n and N needed to account for the $(0.003\ \text{eV})^4$dark energy, assuming $m_{\tilde{G}} \simeq 1$ TeV,

$$\left(\frac{m_Q}{\Lambda_h}\right)^n \sim \begin{cases} 10^{-68} & \text{for SU(3)}_h \\ 10^{-58} & \text{for SU(4)}_h \\ 10^{-48} & \text{for SU(5)}_h \end{cases} \tag{6}$$

For $N = 4$, we obtain $m_Q \simeq 10^{-45}$ GeV, 10^{-16} GeV, and 10^{-7} GeV, respectively, for $n = 1, 2,$ and 3.

This shows that the suppression required can be easily obtained: but it is quite model dependent. In realistic models, however, there are some additional constraints on the parameters that are also relevant for the height of the instanton induced potential. One of them concerns the notorious μ

problem[34] in supergravity. Contributions to the μ term could either come from the superpotenial [34] or the Kähler potential [35]. Understanding the small size of μ requires the presence of a symmetry. The Giudice-Masiero mechanism[35] also relies on a symmetry since here one has to forbid the H_1H_2 term in the superpotential (H_1 and H_2 are the Higgs doublet superfields giving masses to down and up type quarks, respectively). The Peccei-Quinn symmetry is probably the most plausible symmetry for this purpose. It can solve the μ-problem and introduce a very light axion: a possible candidate for cold dark matter(CDM). In hidden sector supergravity models it was shown that

$$W_\mu = \frac{c}{M_P} Q Q^c H_1 H_2 \tag{7}$$

can give a reasonable value of μ. Here c is a constant of order 1, and both Q and Q^c are the left-handed hidden sector quarks transforming like N and $\bar{N}$ of $SU(N)_h$. The scalar superpartners of Q and Q^c are required to condense at a scale near Λ_h without breaking supersymmetry, and this hidden sector squark condensation generates the needed μ term[36]. The hidden sector quarks are not required to condense, otherwise supersymmetry is broken at the hidden sector scale. Gauginos can condense without supersymmetry breaking at the hidden sector scale, but will break supersymmetry through gravity mediation. Eq. (7) is the key equation for this mechanism as it fulfills two roles. Its first is the generation of the μ term through hidden sector squark condensation. Its second role is the generation of a mass for the otherwise massless hidden sector quarks, once the Higgs fields acquire a nonvanishing vacuum expectation value.

As we can see from equation (5) the relevance of this discussion of the μ term for the height of the instanton induced potential becomes evident once we realize that W_μ contributes to the masses of the hidden sector quarks when H_1 and H_2 develop vacuum expectation values(VEV's). Let us now construct an explicit model with a Peccei-Quinn symmetry $U(1)_X$. This symmetry is chosen in such a way that the dimension-3 mass term of Q can be forbidden and m_Q can be made extremely small.

Table I. *The $U(1)_X$ quantum numbers of relevant fields.*

	Q	Q^c	H_1	H_2	q	u^c	d^c
X	1	1	-1	-1	0	1	1

The $U(1)_X$ quantum numbers of the hidden sector quarks Q and Q^c, the Higgs supermultiplets, the ordinary quark doublets q, the up type quarks and down type quarks are shown in Table I. Then, the hidden sector quark obtains mass of order

$$m_Q \simeq 0.64 \times 10^{-14} \sin 2\beta \ [\mathrm{GeV}]. \tag{8}$$

where $\tan\beta = \langle H_2^0 \rangle / \langle H_1^0 \rangle$. Therefore, in view of Eq. (6) two hidden sector

quarks Q_1, Q_1^c, Q_2, Q_2^c in $SU(4)_h$ can generate a reasonable height for the quintessence potential provided that there is no other significant contribution.

The VEV of the squark condensate breaks the global $U(1)$ symmetry spontaneously [d]. The resulting pseudo-Goldstone boson a_h can be identified through

$$\langle \tilde{Q}\tilde{Q}^c \rangle \equiv \tilde{v}^2 \exp\left(i \frac{a_h}{F_h} \right) \tag{9}$$

where $\tilde{v} \sim \Lambda_h$ and $F_h \sim \Lambda_h$. The Kähler potential is expected to respect the $U(1)_X$ symmetry. Therefore, it does not introduce an important contribution to the potential for a_h. The superpotential also respects the $U(1)_X$ symmetry and does not generate a potential for a_h, either.

However, the hidden sector $SU(N)_h$ and QCD $SU(3)_c$ instantons break the $U(1)$ chiral symmetry explicitely and introduce anomalous couplings of a_h. Given the quantum numbers of Table I, we obtain

$$\frac{a_h}{F_h} \frac{2}{32\pi^2} \left[n F_h \tilde{F}_h + 6 F\tilde{F} \right] \tag{10}$$

where n is the number of the hidden sector quarks, and we considered 3 families of standard model fermions. In Eq. (10), we used the abbreviated notations for the hidden sector and QCD anomalies,

$$F_h\tilde{F}_h \equiv \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} F_h^{\mu\nu} F_h^{\rho\sigma}, \quad F\tilde{F} \equiv \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} F^{\mu\nu} F^{\rho\sigma}.$$

The model also opens up the opportunity to solve the strong CP problem by a very light axion. The QCD axion arising from a_h is composite [37] contrary to the axion candidates suggested in Ref. [38]. We employ the nonlinearly realized shift symmetry of the MI-axion a_{MI} which is present in any superstring model without an anomalous $U(1)$ gauge symmetry. The MI-axion coupling to the anomaly is universal

$$\frac{a_{MI}}{F_{MI}} \frac{2}{32\pi^2} \left[F_h\tilde{F}_h + F\tilde{F} \right]. \tag{11}$$

This leads to a rather economic model for quintessence and the solution of the strong CP-problem. We have two axions a_h and a_{MI} both of which couple to the hidden sector anomaly. To pick up the QCD axion a and quintessence a_q, let us define

$$\begin{aligned} a_h = -a_q \sin\alpha + a\cos\alpha, &\quad a_q = -a_h \sin\alpha + a_{MI}\cos\alpha \\ a_{MI} = a_q\cos\alpha + a\sin\alpha, &\quad a = a_h\cos\alpha + a_{MI}\sin\alpha \end{aligned} \tag{12}$$

[d] For completeness we also have to take into account hidden sectro gaugino condensation that leads to a breakdown of a different chiral symmetry. This extra symmetry, however, is explicitly broken by the hidden sector gaugino mass term $-m_{\tilde{G}}\tilde{G}\tilde{G}$. Inclusion of this effect is trivial and the essential features discussed below are not changed because the corresponding meson obtains a huge mass at the order of the $\sqrt{m_{\tilde{G}}\Lambda_h}$.

The instanton effects of Eqs. (10) and (11) generate potentials for the pseudo-Goldstone bosons a_h and a_{MI},[e]

$$V \sim -\lambda_h^4 \cos\left(n\frac{a_h}{F_h}+\frac{a_{MI}}{F_{MI}}\right)-\Lambda_{QCD}^4\cos\left(6\frac{a_h}{F_h}+\frac{a_{MI}}{F_{MI}}\right). \tag{13}$$

where the coefficient Λ_{QCD}^4 is a symbolic representation of $\frac{Z}{(1+Z)^2}f_\pi^2 m_\pi^2$ with $Z=m_u/m_d$. The 2×2 mass square matrix in the a_h and a_{MI} basis becomes

$$M^2=\begin{pmatrix} \frac{6^2\Lambda_{QCD}^4+n^2\lambda_h^4}{F_h^2}, & \frac{6\Lambda_{QCD}^4+n\lambda_h^4}{F_hF_{MI}} \\ \frac{6\Lambda_{QCD}^4+n\lambda_h^4}{F_hF_{MI}}, & \frac{\Lambda_{QCD}^4+\lambda_h^4}{F_{MI}^2} \end{pmatrix} \tag{14}$$

from which the determinant of M^2 is obtained as

$$\text{Det } M^2=(n-6)^2\ \frac{\Lambda_{QCD}^4\lambda_h^4}{F_h^2F_{MI}^2}. \tag{15}$$

For $n=6$ we obtain a flat direction, and hence we assume $n\neq 6$ to generate a tiny potential. The dominant term in Eq. (13) is, of course, the QCD term since the hidden sector term is suppressed by the masses of the hidden sector gauginos and hidden sector quarks. Thus, the argument of the QCD cosine term is defined as the light axion a with mass of order 10^{-5} eV (as a candidate for cold dark matter):

$$\frac{a}{F_a}\simeq\frac{6}{F_h}a_h+\frac{1}{F_{MI}}a_{MI} \tag{16}$$

from which we obtain in the limit $F_{MI}\gg F_h$

$$\sin\alpha=\frac{F_h}{\sqrt{36F_{MI}^2+F_h^2}}\simeq\frac{F_h}{6F_{MI}},\quad \cos\alpha=\frac{6F_{MI}}{\sqrt{36F_{MI}^2+F_h^2}} \tag{17}$$

and determine the light axion(QCD axion) parameters

$$F_a=\frac{F_hF_{MI}}{\sqrt{36F_{MI}^2+F_h^2}}\simeq\frac{F_h}{6},\quad m_a^2\simeq\left(\frac{6\Lambda_{QCD}^2}{F_h}\right)^2. \tag{18}$$

Note that the smaller decay constant (F_a) corresponds to the larger (Λ_{QCD}^4) explicit symmetry breaking scale and the larger decay constant (F_q) corresponds to the smaller (λ_h^4) explicit symmetry breaking scale. From Eqs. (15) and (18), we obtain the mass of the quintaxion a_q

$$m_q^2\simeq\left(\frac{(n-6)\lambda_h^2}{6F_{MI}}\right)^2. \tag{19}$$

[e]The runaway potential of the dilaton S and $\langle\tilde{Q}\tilde{Q}^c\rangle$ is expected to be stabilized at zero cosmological constant. The potential V here arises from the imaginary parts of S and $\tilde{Q}\tilde{Q}^c$.

The quintaxion decay constant is close to F_{MI}

$$F_q \simeq \frac{6}{|6-n|} F_{MI}. \tag{20}$$

Since F_{MI} is near the Planck scale[33], we obtain a large axion decay constant near that scale, as required for quintessence[21].

In axion models, it is important to know the domain wall number and the axion coupling to matter fermions. On one hand one has to worry about a possible domain wall problem[39] in standard big bang cosmology. However, in inflationary models with the reheating temperature below 10^9 GeV required from the gravitino constraint, this old domain wall problem is only of academic interest. The model we presented here has the domain wall number one, as the MI-axion has the domain wall number one[40]. The axion-matter coupling in our model is the same as those of the DFSZ [41,42] model because the symmetry $U(1)_X$ assigns the quantum numbers of the DFSZ model as shown in Table I.

Invisible axion models that give suitable candidates for cold dark matter (CDM) of the universe have to answer the question: "Why is F_a near the scale of the CDM axion?" Besides being economic, the model presented here gives an explanation for this scale problem. The breaking scale of the Peccei-Quinn symmetry is the scale of the hidden sector scalar-quark condensate. The scale for this condensate is at the intermediate scale as the requirement for the appearance of the 100 GeV scale in the observable sector should arise from gravity mediation. In addition, the seed for the μ term is at this scale, and this gives the required axion decay constant of the order of 10^{12} GeV.

We thus have constructed a simple scheme that combines a mechanism for cold dark matter with one for the dark energy of the universe. The model contains a light CDM axion (to solve the strong CP problem) with decay constant $F_a \sim 10^{12}$ GeV (through hidden sector squark condensation) and a quintaxion (reponsible for dark energy) with $F_q \sim 10^{18}$ GeV (as expected for the MI-axion). The potential of the quintaxion is so shallow because of the smallness of the hidden sector quark masses which in turn is connected to the generation of the μ term. The main formula that is reponsible for the mechanism discussed here is eq. (7). It gives the suitable value for the μ term as a result of the condensation of hidden sector squarks, but it is also reponsible for the mass of the hidden sector quarks that appear once the Higgs bosons receive a nontrivial vacuum expectation value. It is this multiple see-saw mechanism that leads to the small value of the vacuum energy of $(0.003\text{ eV})^4$ and the extremely small value of the quintaxion mass of 10^{-32} eV.

Acknowledgements

This work was partly supported by the European Community's Human Potential Programme under contracts HPRN–CT–2000–00131 Quantum Space-

time, HPRN–CT–2000–00148 Physics Across the Present Energy Frontier and HPRN–CT–2000–00152 Supersymmetry and the Early Universe.

References

1. H. P. Nilles, Phys. Lett. **B115** (1982) 193,
2. H. P. Nilles, Nucl. Phys. B **217**, 366 (1983).
3. S. Ferrara, L. Girardello and H. P. Nilles, Phys. Lett. B **125**, 457 (1983).
4. J. Polonyi, *Hungary Central Inst Res - KFKI-77-93 (77).*
5. A. H. Chamseddine, R. Arnowitt and P. Nath, Phys. Rev. Lett. **49**, 970 (1982).
6. R. Barbieri, S. Ferrara and C. A. Savoy, Phys. Lett. B **119**, 343 (1982).
7. H. P. Nilles, M. Srednicki and D. Wyler, Phys. Lett. B **120**, 346 (1983).
8. D. Gross, J. A. Harvey, E. Martinec, and R. Rohm, Nucl. Phys. **B256** (1985) 253.
9. J. P. Derendinger, L. E. Ibanez and H. P. Nilles, Phys. Lett. B **155**, 65 (1985).
10. J. P. Derendinger, L. E. Ibanez and H. P. Nilles, Nucl. Phys. B **267**, 365 (1986).
11. M. Dine, R. Rohm, N. Seiberg and E. Witten, Phys. Lett. B **156**, 55 (1985).
12. P. Horava and E. Witten, Nucl. Phys. B **460**, 506 (1996) [hep-th/9510209].
13. P. Horava, Phys. Rev. D **54**, 7561 (1996) [hep-th/9608019].
14. H. P. Nilles, M. Olechowski and M. Yamaguchi, Phys. Lett. B **415**, 24 (1997) [hep-th/9707143].
15. H. P. Nilles, M. Olechowski and M. Yamaguchi, Nucl. Phys. B **530**, 43 (1998) [hep-th/9801030].
16. H. P. Nilles, Phys. Rept. **110** (1984) 1.
17. H. P. Nilles, Nucl. Phys. Proc. Suppl. **101** (2001) 237, e-Print Archive: hep-ph/0106063.
18. E. Witten, Phys. Lett. **B149** (1984) 351.
19. J. Preskill, M. B. Wise, and F. Wilczek, Phys. Lett. **B120** (1983) 127; L. F. Abbott and P. Sikivie, Phys. Lett. **B120** (1983) 133; M. Dine and W. Fischler, Phys. Lett. **B120** (1983) 137.
20. S. Perlmutter et al., Astrophysical J. 517 (1999) 565.
21. J. A. Frieman, C. T. Hill, A. Stebins, and I. Waga, Phys. Rev. Lett. **75** (1995) 2077;
22. J. E. Kim, JHEP **9905** (1999) 022.
23. J. E. Kim, JHEP **0006** (2000) 016; K. Choi, Phys. Rev. **D62** (2000) 043509.
24. M. Bronstein, *Physikalische Zeitschrift Sowjet Union* **3**, 73 (1933); M. Özer and M. O. Taha, Nucl. Phys. **B287** (1987) 797; B. Ratra and P. J.

E. Peebles, Phys. Rev. **D37** (1988) 3406; C. Wetterich, Nucl. Phys. **B302** (1988) 645; H. Gies and C. Wetterich, hep-ph/0205226; J. A. Frieman, C. T. Hill and R. Watkins, Phys. Rev. **D46** (1992) 1226; R. Caldwell, R. Dave and P. J. Steinhardt, Phys. Rev. Lett. **80** (1998) 1582; P. Binetruy, Phys. Rev. **D60** (1999) 063502; C. Kolda and D. H. Lyth, Phys. Lett. **B458** (1999) 197; T. Chiba, Phys. Rev. **D60** (1999) 083508; P. Brax and J. Martin, Phys. Lett. **B468** (1999) 40; A. Masiero, M. Pietroni and F. Rosati, Phys. Rev. **D61** (2000) 023504; M. C. Bento and O. Bertolami, *Gen. Rel. Grav.* **31** (1999) 1461; F. Perrotta, C. Baccigalupi and S. Matarrase, Phys. Rev. **D61** (2000) 023507; A. Arbey, J. Lesgourgues and P. Salati, Phys. Rev. **D65** (2002) 083514.

25. For recent works on ultra light pseudo Goldstone bosons, see, A. Albrecht, C. P. Burgess, F. Ravndal and C. Skordis, Phys. Rev. **D65** (2002) 123507; C. T. Hill and A. K. Leibovich, hep-ph/0205237.
26. J. E. Kim and H. P. Nilles, Phys. Lett. B **553** (2003) 1 [arXiv:hep-ph/0210402].
27. S. M. Carroll, Phys. Rev. Lett. **81** (1998) 3067 [arXiv:astro-ph/9806099].
28. J. E. Kim, Phys. Rep. **150** (1987) 1; H. Y. Cheng, Phys. Rep. **158** (1988) 1; R. D. Peccei, in *CP Violation*, C. Jarlskog ed., World Scientific, 1989, p. 503.
29. M. Veltman, Phys. Rev. Lett. **34** (1975) 777.
30. S. Weinberg, Rev. Mod. Phys. **61** (1989) 1.
31. J. E. Kim, B. Kyae, and H. M. Lee, Phys. Rev. Lett. **86** (2001) 4223; Nucl. Phys. **B613** (2001) 306.
32. A. D. Linde and R. Kallosh, hep-th/0208157.
33. K. Choi and J. E. Kim, Phys. Lett. **B154** (1985) 393.
34. J. E. Kim and H. P. Nilles, Phys. Lett. **B138** (1984) 150.
35. G. Giudice and A. Masiero, Phys. Lett. **B206** (1988) 480.
36. E. J. Chun, J. E. Kim, and H. P. Nilles, Nucl. Phys. **B370** (1992) 105.
37. J. E. Kim, Phys. Rev. **D31** (1985) 1733.
38. J. E. Kim, Phys. Rev. Lett. **43** (1979) 103; M. Dine, W. Fischler and M. Srednicki, Phys. Lett. **B104** (1981) 199; M. A. Shifman, V. I. Vainstein and V. I. Zakharov, Nucl. Phys. **B166** (1980) 4933; A. Zhitniskii, *Sov. J. Nucl. Phys.* **31** (1980) 260.
39. P. Sikivie, Phys. Rev. Lett. **48** (1982) 1156.
40. K. Choi and J. E. Kim, Phys. Rev. Lett. **55** (1985) 2637.
41. A. R. Zhitnitsky, Sov. J. Nucl. Phys. **31** (1980) 260 [Yad. Fiz. **31** (1980) 497].
42. M. Dine, W. Fischler and M. Srednicki, Phys. Lett. B **104** (1981) 199.